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Periodic Magnetoresistance Oscillations in Side-Gated Quantum Dots

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Abstract. We fabricated side-gated quantum-dot structures on a GaAs/AlGaAs single heterostructure and measured their magnetoresistance at low temperature. We observed that oscillations appear almost periodic in B for a lower magnetic field region. We find that the oscillation period is fairly independent of the structure width. The experimental magnetoconductance are compared with numerical results.

1. Introduction

There has been growing interest in understanding and controlling the quantum properties of semiconductor quantum structures, with possible application to quantum computing and novel electronic devices [1, 2]. Conductance measurement at low temperature is one of major experimental methods used for characterizing the quantum properties of such structures. It has been pointed out that the conductance of electrons in a ballistic quantum wire with abrupt geometrical changes at the both ends shows quantum oscillations at low temperatures under zero magnetic field [3, 4]. Resonant states are formed when the channel length is an integer multiple of half of the electron wavelength, resulting in an oscillatory structure in the conductance. Under magnetic fields, Aharonov-Bohm-type oscillations are also predicted in a ballistic quantum wire with a thin potential tunnel-barrier [5, 6]. In the present study, we have fabricated side-gated ballistic quantum-dot structures on a GaAs/AlGaAs single heterostructure and studied their transport characteristics under magnetic fields for investigating the effect of coupling strength between the quantum-dot and reservoir states [7, 8].

2. Sample and Experimental Details

To control the coupling strength between the quantum-dot and reservoir states, we fabricated a side-gated quantum-dot structure whose schematic diagram is given in Fig. 1. The structure is fabricated on a GaAs/$Al_{0.265}Ga_{0.735}As$ single heterostructure with electron beam lithography and wet chemical etching. The elastic mean free path and sheet electron density are estimated to be $1.4\,\mu$m and $3.5 \times 10^{11}\,\mathrm{cm}^{-2}$, respectively, at $T = 77\,\mathrm{K}$ before processing. The side-gated quantum-dot structure consists of a center quantum-dot region ($1,300\,$nm-length and $1,000\,$nm-width) connected to two large reservoirs through two leads ($620\,$nm-width) and two types of side-gates, which are named as lead-gate and dot-gate (see Fig. 1). By applying lead-gate voltage, V_{L}, the coupling strength between the quantum-dot and reservoir states can be controlled. The dot-gate voltage, V_{D}, mainly affects the quantum-dot width. The sample was

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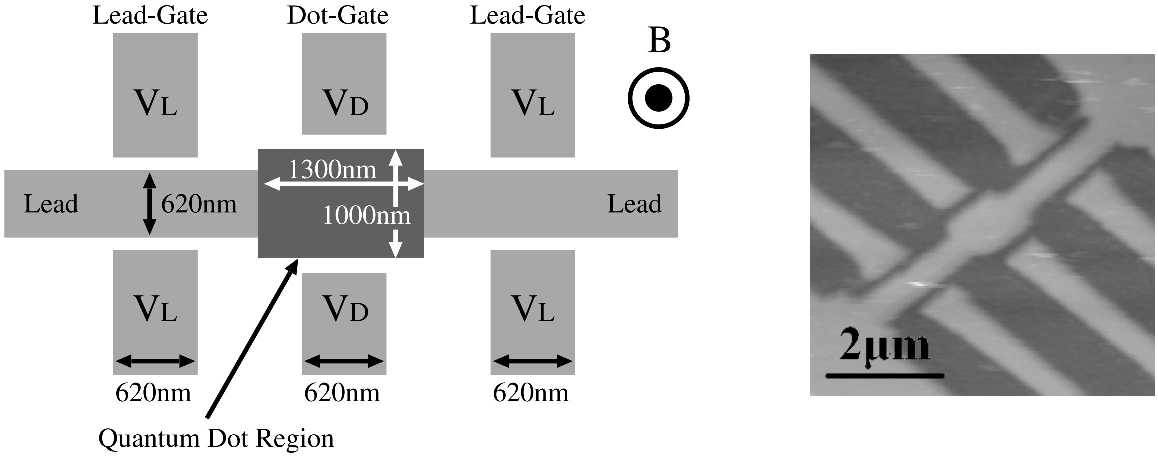

Figure 1. Schematic diagram of the side-gated quantum-dot structure (left) and AFM image of the sample (right).

mounted on a variable-temperature stage in the vacuum space of a cryostat. Magnetic field was applied perpendicular to the hetero-interface. Conductance measurements were carried out using a standard lock-in technique.

3. Results and Discussion

Figure 2 shows magnetoresistance at $T = 1.7\,\mathrm{K}$ with varying V_{L} from $0\,\mathrm{V}$ to $-1.0\,\mathrm{V}$ at $V_{\mathrm{D}} = 0\,\mathrm{V}$. For $B > 1\,\mathrm{T}$ (not shown in Fig. 2), we observed clear Shubnikov de Haas oscillations, from which we estimated the sheet electron density as $6.5 \times 10^{11}\,\mathrm{cm}^{-2}$. For $B < 1\,\mathrm{T}$, we observed

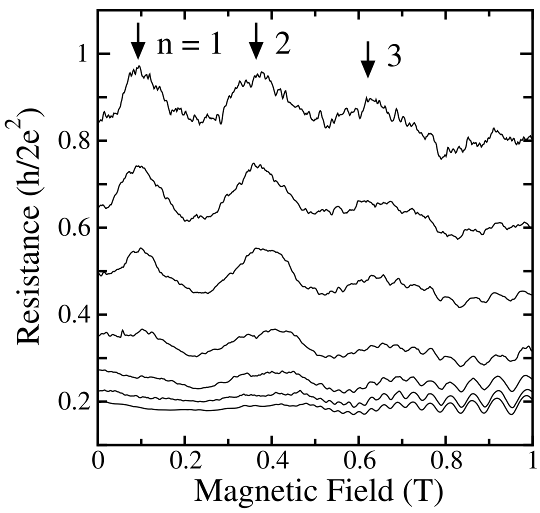

Figure 2. Magnetoresistance at $T = 1.7\,\mathrm{K}$ for lead-gate voltage, $V_{\mathrm{L}} = 0\,\mathrm{V}$ (bottom), $-0.2\,\mathrm{V}$, $-0.4\,\mathrm{V}$, $-0.6\,\mathrm{V}$, $-0.8\,\mathrm{V}$, $-0.9\,\mathrm{V}$, and $-1.0\,\mathrm{V}$ (top) at $V_{\mathrm{D}} = 0\,\mathrm{V}$. Arrows indicate the peak position.

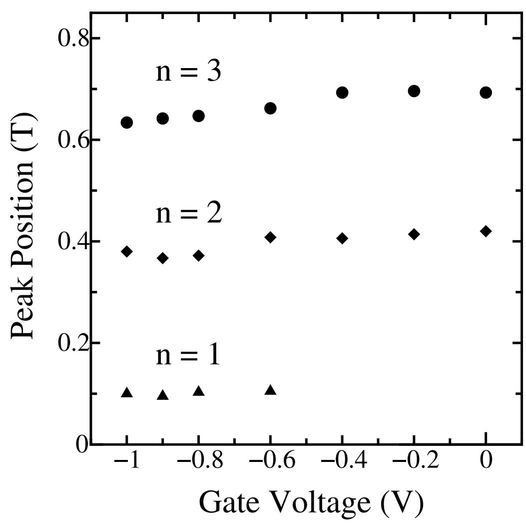

Figure 3. Lead-gate voltage dependence of the peak position of the magnetoresistance. The oscillation period, $\Delta B \approx 0.27\,\mathrm{T}$, is almost independent of the gate voltage.

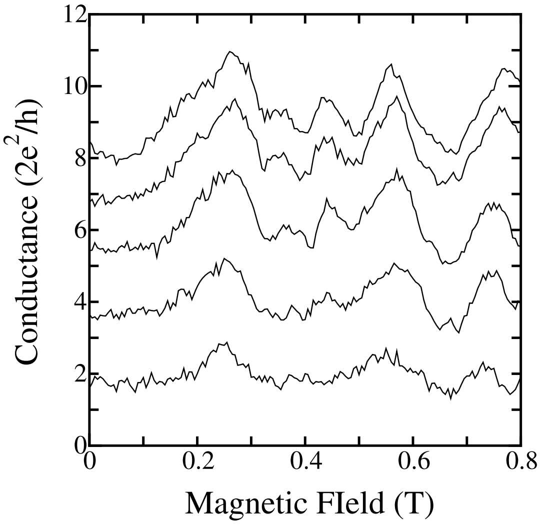

Figure 4. Calculated magnetoconductance at $T = 1.7\,\mathrm{K}$ for lead width, $W_\mathrm{L} = 200\,\mathrm{nm}$ (top), 180 nm, 140 nm, 100 nm, and 60 nm (bottom). Quantum-dot width is fixed to be $W_\mathrm{D} = 880\,\mathrm{nm}$.

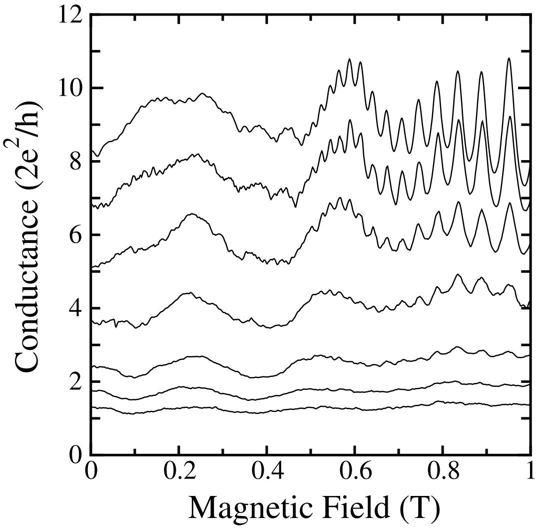

Figure 5. Magnetoconductance at $T = 1.7\,\mathrm{K}$ for lead-gate voltage, $V_\mathrm{L} = 0\,\mathrm{V}$ (top), $-0.2\,\mathrm{V}$, $-0.4\,\mathrm{V}$, $-0.6\,\mathrm{V}$, $-0.8\,\mathrm{V}$, $-0.9\,\mathrm{V}$, and $-1.0\,\mathrm{V}$ (bottom) at $V_\mathrm{D} = 0\,\mathrm{V}$. Note that series resistance $1\,\mathrm{k}\Omega$ has been subtracted from the experimental magnetoresistance.

an oscillatory structure as indicated by arrows in Fig. 2. In Fig. 3, we show V_L dependence of the peak position. We find that the oscillations appear almost periodic in B and the oscillation period, ΔB, is fairly independent of V_L ($\Delta B \approx 0.27\,\mathrm{T}$). Since V_L primarily affects the coupling strength between the quantum-dot and reservoir states, the oscillatory structure of the magnetoresistance is considered to be originated in the quantum-dot geometry. To obtain further insight of the origin of the oscillation, we carried out numerical simulation using a stabilized version of the transfer matrix approach [9, 10]. We used the following parameters in the calculation; Fermi energy, $E_F = 23\,\mathrm{meV}$ and depletion width, $d = 210\,\mathrm{nm}$. To simulate the effects of the lead-gate voltage, we change the lead width, W_L, in the calculation (see the inset of Fig. 6 for W_L). Figure 4 shows calculated magnetoconductance with varying W_L from 200 nm to 60 nm for a fixed quantum-dot width, $W_\mathrm{D} = 880\,\mathrm{nm}$ at $T = 1.7\,\mathrm{K}$. We obtain reasonable agreement between the calculated magnetoconductance and the experimental results (Fig. 5), when series resistance has been subtracted from the experimental magnetoresistance. This confirms that the oscillation is originated in the quantum-dot geometry and its period is almost independent of the lead width, e.g., the coupling strength between the quantum-dot and outside reservoir states hardly affects the oscillation period.

Next, we examine the effects of the quantum-dot width on the oscillation. Figure 6 shows calculated magnetoconductance with varying quantum-dot width, W_D, from 880 nm to 640 nm for a fixed lead-width, $W_\mathrm{L} = 200\,\mathrm{nm}$ at $T = 1.7\,\mathrm{K}$. We find that W_D dependence of the conductance peak position is very weak. Especially the conductance peak at $B \approx 0.25\,\mathrm{T}$ is hardly affected by W_D. The feature is, therefore, considered to be mainly determined by the quantum-dot length. This suggests that the oscillation is not associated with the Aharonov-Bohm-type effects. In Fig. 7, we show the experimental results of magnetoconductance at $T = 1.7\,\mathrm{K}$ with V_D varying from 0 V to $-1.0\,\mathrm{V}$ for $V_\mathrm{L} = 0\,\mathrm{V}$. The experimental results are consistent with the numerical results on the point that V_D dependence of the peak position

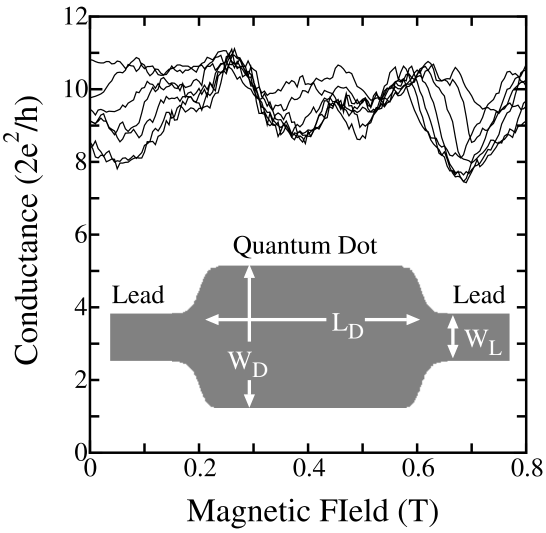

Figure 6. Calculated magnetoconductance at $T = 1.7\,\mathrm{K}$ for quantum-dot width, $W_\mathrm{D} = 880\,\mathrm{nm}$, 840 nm, 800 nm, 760 nm, 720 nm, 680 nm, and 640 nm. Lead width is fixed to be $W_\mathrm{L} = 200\,\mathrm{nm}$. The inset shows a schematic diagram of a simulated structure.

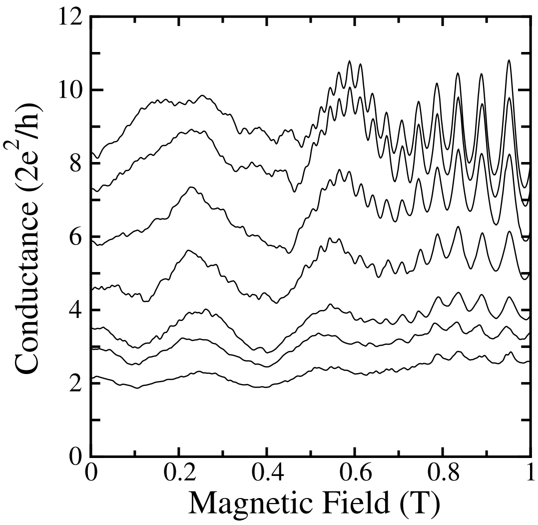

Figure 7. Magnetoconductance at $T = 1.7\,\mathrm{K}$ for dot-gate voltage, $V_\mathrm{D} = 0\,\mathrm{V}$ (top), $-0.2\,\mathrm{V}$, $-0.4\,\mathrm{V}$, $-0.6\,\mathrm{V}$, $-0.8\,\mathrm{V}$, $-0.9\,\mathrm{V}$, and $-1.0\,\mathrm{V}$ (bottom) at $V_\mathrm{L} = 0\,\mathrm{V}$. Note that series resistance $1\,\mathrm{k\Omega}$ has been subtracted from the experimental magnetoresistance.

is very weak. The experimental conductance at $B = 0\,\mathrm{T}$, however, decreases with V_D, while the theoretical conductance slightly increases as W_D decreases. We attribute this difference to the fact that the dot-gate voltage affects not only the quantum-dot region but also the leads. Although the present results indicate that the oscillations are connected with the electron motion along the transport direction, the details are still unclear and under study.

4. Summary

In summary, to study the effect of coupling strength between quantum-dot and outside reservoir states, we have fabricated side-gated quantum-dot structures on a GaAs/AlGaAs single heterostructure and measured their magnetoresistance at $T = 1.7\,\mathrm{K}$. We observed that magnetoresistance oscillations appear almost periodic in B for $B < 1\,\mathrm{T}$. We find that the oscillation period is fairly independent of the structure width.

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